

Spin-dependent electron transport through a ferromagnetic domain wall

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Recent advances in spin-sensitive electronics made it possible to realize spin-dependent electron transport in mesoscopic systems. Utilizing the carrier's spin degrees of freedom in addition to their charge opens the possibilities of new spintronic devices.¹⁾ The injection of spin polarized electrons in mesoscopic systems can be achieved by a current from a ferromagnetic lead. One of the most interesting transport properties in such systems is the magnetoresistance induced by the electron scattering by the spatial variation of the magnetization, namely the domain wall, controlled by the external field. The width of a domain wall can now be directly measured and geometrically controlled.²⁾ For the application to the actual devices, it is important to extend the understanding of spin-dependent transport through such a controllable domain wall system. In this contribution, we present a theoretical study of spin-dependent transport through a ferromagnetic domain wall. We calculate the conductance of this system by using the transfer matrix method³⁾ and extending it to include the spin degrees of freedom.

We have studied the behavior of the conductance as a function of the geometry and strength of the domain wall. We have considered three kinds of domain walls, namely Ising, XY and Heisenberg types. With an increase of the number of components of the exchange coupling, we have observed that the variance of the conductance becomes half. As the strength of the domain wall magnetization is increased, negative magnetoresistance and a change of the conductance fluctuation are observed.

We consider a two dimensional (2D) system connected to two electrodes. The 2D system is constructed in the x and y directions and current flows in the x direction. An exchange interaction between the electron spin and the static local spin exists in the system. The one-electron Hamiltonian is

$$H = - \sum_{\langle i,j \rangle} c_i^+ c_j + \sum_i W_i c_i^+ c_i - J \sum_i c_i^+ \boldsymbol{\sigma} c_i \cdot \mathbf{S}(x), \quad (1)$$

where c_i^+ (c_i) denotes the creation (annihilation) operator of electron at the site i on the 2D square lattice. The transfer energy is taken to be the unit energy. Energies W_i denote the random potential distributed independently and uniformly in the range $[-W/2, W/2]$. The hopping is restricted to nearest neighbors. $\boldsymbol{\sigma}$ is the Pauli

spin matrix and $\mathbf{S}(x)$ is the local spin which has a spatial dependence of a domain wall. Three types of domain walls, Ising, XY and Heisenberg, are modelled as follows: for the Ising domain wall we set

$$S_x(x) = 0, S_y(x) = 0, \\ S_z(x) = \begin{cases} S_0 & \text{for } x \leq L, \\ S_0 \cos(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ S_0 \cos(N\pi) & \text{for } x \geq L + N\lambda, \end{cases}$$

where L is the position of the beginning of the domain wall, N the number of rotations and λ the length of the domain wall. An XY domain wall is given by

$$S_x(x) = 0, \\ S_y(x) = \begin{cases} S_0 \sin(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ 0 & \text{for otherwise,} \end{cases} \\ S_z(x) = \begin{cases} S_0 & \text{for } x \leq L, \\ S_0 \cos(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ S_0 \cos(N\pi) & \text{for } x \geq L + N\lambda. \end{cases}$$

Similarly, a Heisenberg domain wall is modelled as

$$S_x(x) = \begin{cases} S_0 \sin(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ 0 & \text{for otherwise,} \end{cases} \\ S_y(x) = \begin{cases} S_0 \cos(\frac{\pi(x-L)}{\lambda}) \sin(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ 0 & \text{for otherwise.} \end{cases} \\ S_z(x) = \begin{cases} S_0 & \text{for } x \leq L, \\ S_0 \cos^2(\frac{\pi(x-L)}{\lambda}) & \text{for } L < x < L + N\lambda, \\ S_0 \cos(N\pi) & \text{for } x \geq L + N\lambda. \end{cases}$$

The conductance G is given by Landauer's formula as

$$G = \frac{e^2}{h} \text{tr}(tt^+) = \frac{e^2}{h} \sum_i \tau_i, \quad (2)$$

where t is the transfer matrix³⁾ including the spin degree of freedom and τ_i the transmission eigenvalue.

In the preset simulation, the system size is 30×30 in units of lattice spacing, W is set to be 3.0, and at least 50,000 samples are taken for each ensemble. $JS_0 = \tilde{J} = 3.0$ for the three types of domain walls, and $\lambda = 10$ and $L = 1$.

In Fig. 1 we show variance of conductance of these systems with $N = 1$. When $\tilde{J} = 0$, there is no magnetic scattering and the variance is close to that expected for

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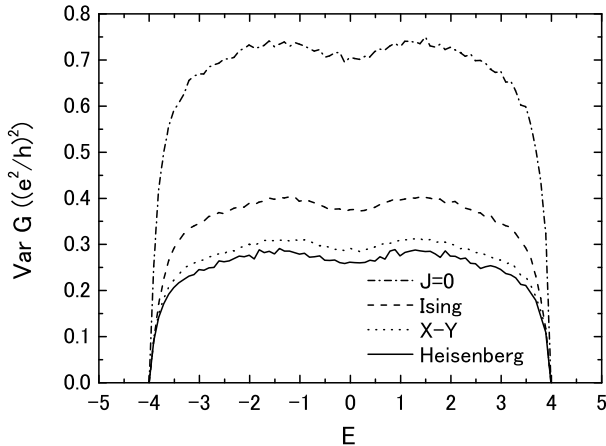


Fig. 1. Variance of the conductance for $N = 1$. Other parameters are $W = 3.0$, $\lambda = 10$ and $L = 1$.

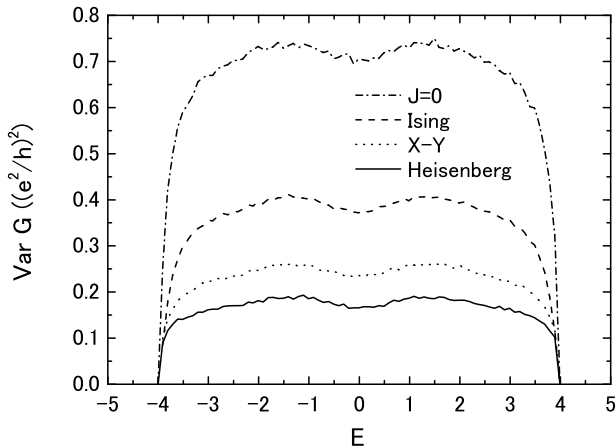


Fig. 2. Variance of the conductance for $N = 2$. Other parameter is the same with Fig. 1.

the universal conductance fluctuation of orthogonal systems.⁴⁾ For an Ising domain wall, spin-up and spin-down electrons are described by different wave functions, because the exchange field of domain wall breaks the spin degeneracy. Therefore, the value of variance becomes half of the case for $\tilde{J} = 0$.

While the Ising domain wall does not rotate the spin direction, the spin flip process occurs in XY and Heisenberg domain wall models. In these cases, the variance of two systems are reduced by the Ising domain wall case as shown in Fig. 1.

From the point of view of the symmetry of the Hamiltonian, the XY domain wall model is classified into the orthogonal class, while the Heisenberg domain wall model is classified into the unitary. In Fig. 1, the difference of the variance of the conductance between XY and

Heisenberg cases is small, but for $N = 2$ the reduction of the variance for the Heisenberg model is prominent.

The results of the reduction of the variance are interpreted as follows. The conductance fluctuation is determined by the spectral statistics of the transmission

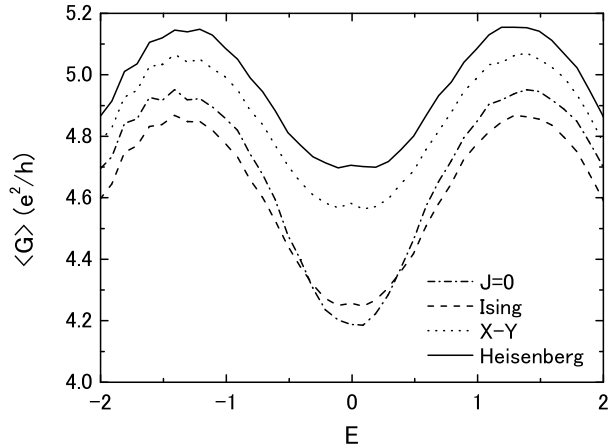


Fig. 3. Average of the conductance for $N = 2$. Other parameter is the same with Fig. 1.

eigenvalues τ . Let us denote the variance of $\sum_i \tau_i$ for orthogonal 2D class as V_{2DO} and the $G/(e^2/h) = \tilde{G}$. Then due to the spin degeneracy in the case of $\tilde{J} = 0$, $\text{Var } \tilde{G} = 4V_{2DO}$. For sufficiently strong Ising domain walls, the up and down spin states form an independent ensemble and $\text{Var } \tilde{G} = 2V_{2DO}$. In the presence of XY domain walls, the variance is simply given by $\text{Var } \tilde{G} = V_{2DO}$. Systems with Heisenberg domain walls belong to the unitary class and $\text{Var } \tilde{G} = \frac{1}{2}V_{2DO}$.

Our results also show that the domain walls suppress the weak localization effect due to impurity scattering. Fig. 3 shows the average conductance. System parameters are the same as in Fig. 2. We observe increases of conductance in the presence of XY or Heisenberg types domain walls.

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